AD-A033 574

AFML-TR-76-174

A CRACK GROWTH GAGE FOR ASSESSING FLAW GROWTH POTENTIAL IN STRUCTURAL COMPONENTS

METALS BEHAVIOR BRANCH
METALS AND CERAMICS DIVISION

OCTOBER 1976

TECHNICAL REPORT AFML-TR-76-174
FINAL REPORT FOR PERIOD MARCH 1976 - JULY 1976

AIR FORCE MATERIALS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This report has been reviewed by the Information Office (IO) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

R.L. Crane
R.L. CRANE
Nondestructive Evaluation Branch
Air Force Materials Laboratory

A.F. Grandt
A.F. GRANDT
Metals Behavior Branch
Air Force Materials Laboratory

J.P. Gallagher
J.P. GALLAGHER
Structural Integrity Branch
Air Force Flight Dynamics Laboratory

FOR THE COMMANDER

Vincent J. Russo
VINCENT J. RUSSO
Chief, Metals Behavior Branch
Metals and Ceramics Division
Air Force Materials Laboratory

Copies of this report should not be returned unless return is required by security considerations, contractural obligations, or notice on a specific document.

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER AFML-TR-76-174	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A CRACK GROWTH GAGE FOR ASSESSING FLAW GROWTH POTENTIAL IN STRUCTURAL COMPONENTS		5. TYPE OF REPORT & PERIOD COVERED March 1976-July 1976 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) R. L. Crane A. F. Grandt J. P. Gallagher		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Air Force Materials Laboratory & Air Force Flight Dynamics Laboratory Air Force Systems Command Wright-Patterson Air Force Base, Ohio		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Project No. 2279
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Materials Laboratory Air Force Systems Command Wright-Patterson Air Force Base, Ohio		12. REPORT DATE October 1976 13. NUMBER OF PAGES 21
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release, distribution is unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Nondestructive Evaluation, Crack Growth, Life Prediction

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A new concept for monitoring the potential for damage accumulation in structural materials is presented. Briefly, the method proposed is to install a preflawed gage on a critical component and to monitor its flaw growth nondestructively. The relationship between this flaw size and the potential flaw in the structure is derived using linear elastic fracture mechanics principles. Experimental flaw growth data produced by an aircraft spectrum was used to demonstrate the validity of a degenerate case of this concept. A discussion is also presented to show how this method could be implemented in fulfillment of the Mil-Std-1530 requirement to track potential flaw growth.

FOREWORD

This technical report was prepared by the Metals Behavior Branch, Metals and Ceramics Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio. The research was conducted under Project No. 2279, Task No. 22790101 during the period March 1976 to July 1976.

The author would like to acknowledge the significant contributions of Mr. Jim G. Paine, Systems Research Laboratories, Dayton, Ohio in the experimental portion of the investigation.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

SECTION I

INTRODUCTION

It is the objective of this Technical Report to describe a new concept for monitoring the potential for damage accumulation in structural materials. A recent change in Air Force policy is the requirement to track crack growth potential in a manner that realistically includes the effects of overloads, hold times, environment, etc. This specific requirement is covered in U.S.A.F. document MIL-STD-1530A(1) paragraphs 5.4.5, which states "...the objective of the individual airplane tracking program shall be to predict the potential flaw growth in critical areas of each airframe that is keyed to damage growth limits of MIL-A-83444..." and "...tracking analysis method shall be developed to establish and adjust inspection and repair intervals for each critical area of the airframe based on the individual airplane usage data." A great deal of prior work has gone into research and development of techniques, procedures, and instruments to assess structural damage accumulation (References 1-6). The many instruments that were developed to facilitate damage accumulation tracking are commonly referred to as "fatigue gages," see for example Reference 4. These gages have not been generally successful because it was not possible to relate the gage response to accumulation of structural damage. The approach suggested here differs from all previous methods in that a precracked specimen or "gage" is mounted on the load bearing member, shown schematically in Figure 1, where it experiences the same displacement and environmental history as the member. Therefore, the gage crack grows in a manner relatable to those possibly in the structure. Linear elastic fracture mechanics analysis is then employed to relate crack growth in the gage with the growth of a real or assumed initial flaw located in the structure. Crack growth in the gage can then be conveniently examined with NDE techniques during service for an indication of growth of the assumed structural defect. Moreover, as shown schematically in Figure 2, this relationship permits allowable maximums for the structural crack size (based on safety criteria or repair economics) to specify corresponding gage limits.

One of us considered this gage for use on composite structures where the two principal mechanisms of strength loss, mechanical fatigue and environmental degradation, interact in a complex manner (References 7-9).

Since laboratory experiments have shown that even simple moist atmospheric exposure can reduce the strength and modulus of a composite dramatically, and because it is not possible to nondestructively predict service life of such components, designers have been forced to use this new material only in quite conservative designs. A gage that would integrate the effects of both the environment and loading on a real time basis and permit frequent nondestructive examination would be an obvious asset to both the designer and user of composite structures. With proper design and interpretation such a gage would permit the prediction of residual service life for composite structures, thus increasing the confidence in their usage.

In this Technical Report the analytical expressions relating the cracks in a metal structure and gage are derived and sample calculations are made for various flaw geometries. An experimental verification of a portion of the mathematical model is also presented. Unfortunately, it was not possible here to develop a similar model for composite structural components because of the lack of flaw growth laws for these materials. This deficiency will be covered at the end of this report.

SECTION II

ANALYSIS

Considering Figure 1, assume that a small precracked coupon (crack length = a_g) is fixed along its ends to a large structural component containing a crack of length a_s. The problem here is to correlate growth of a_s with extension of a_g. In all subsequent discussion, it will be assumed that linear elastic fracture mechanics conditions are satisfied in both the gage and structure during service loading. In addition, the gage is sufficiently small that its attachment does not change the stresses in the structure.

<u>Relation Between Gage and Structural Loads</u>

The objective here is to determine the gage load P caused by application of the uniform structural stress σ_s shown in Figure 1. Since the gage endpoints are fixed to the structure, the total displacement δ along the gage length L equals that of the attached structure and is given by

$$\delta = \int_o^L \varepsilon_s dL = \frac{\sigma_s L}{E_s} \tag{1}$$

Here ε_s is the uniform strain over L, and E_s is the modulus of elasticity for the structure. Similarly, the gage has a component of displacement δ' given by

$$\delta' = \frac{PL}{BWE_g} \tag{2}$$

where B, W, and E_g are, respectively, the thickness, width, and elastic modulus of the gage.

The gage also has another component of displacement δ'' due to the presence of the flaw. Using the compliance concept outlined in Reference 10, this additional deflection is given by

$$\delta'' = P\lambda \tag{3}$$

where λ is the crack compliance related to the strain energy release rate G, and the stress intensity factor K_g of the gage by the plain strain relationship

$$G = \frac{P^2}{2B} \frac{\partial\lambda}{\partial a_g} = \frac{1-\nu^2}{E_g} K_g^2 \tag{4}$$

Here ν is Poisson's ratio for the gage. For plane stress conditions, $\nu=0$ in Eq. (4). Expressing the stress intensity factor in the form

$$K = \frac{P}{BW} \sqrt{\pi a}\ \beta \tag{5}$$

where β is a dimensionless geometry factor which can depend on crack length, Eqs. (4) and (5) reduce to

$$\lambda = \frac{2(1-\nu^2)\pi}{E_g BW^2} \int_0^{a_g} a\beta_g^2 da \tag{6}$$

Thus, the displacement of the gage is given by

$$\delta = \delta' + \delta'' = \frac{PL}{E_g BW} + P\lambda = \frac{\sigma_s L}{E_s} \tag{7}$$

which when solved for gage load with Eq. (6) becomes

$$P = \sigma_s BW \left\{ \frac{E_g}{E_s} \left[\frac{L}{L + \frac{2(1-\nu^2)\pi}{W} \int_0^{a_g} a\beta_g da} \right] \right\} = \sigma_s BWf \tag{8}$$

where f is the bracketed quantity defined by Eq. (8).

Thus the load in the cracked gage is directly related to the uniform gross stress in the structure. This uniform stress is the same stress that influences the crack growth behavior at the structural detail of interest. It now remains to describe how the crack growth behavior of the detail is related to that in the gage, i.e., to provide the transfer function.

<u>Gage and Structural Crack Relation</u>

$$\frac{da}{dF} = C\overline{K}^m \tag{9}$$

where da/dF is the average crack extension per block of service usage (e.g., an aircraft flight) and C and m are empirical constants. The parameter $\overline{K}$ is a stress intensity factor that senses the influence of stress history on the crack growth process. As such, $\overline{K}$ is normally obtained by multiplying a stress history characterizing parameter (e.g., $\bar{\sigma}$ = rms stress range) by the stress intensity factor coefficient for the geometry of interest. For the structure, $\overline{K}$ would be

$$\overline{K} = \bar{\sigma} \left(\frac{K}{\sigma}\right) = \bar{\sigma}_s \sqrt{\pi a_s} \; \beta_s \tag{10}$$

Now assume that both the gage and structure are made from material which have the same Paris exponent m in Eq. (9). Using the fact that both gage and structure see the same number of loading blocks F, integrating Eq. (9) for a fixed number of flights with Eq. (5) and Eq. (10) yields

$$F = \int_{a_{os}}^{a_s} \frac{da}{C_s(\bar{\sigma}_s \sqrt{\pi a} \; \beta_s)^m} = \int_{a_{og}}^{a_g} \frac{da}{C_g(\frac{\bar{P}}{BW}) \; \sqrt{\pi a} \; \beta_g)^m} \tag{11}$$

which reduces by employing Eq. (8) and canceling like quantities to

$$\frac{C_g}{C_s} \int_{a_{os}}^{a_s} \frac{da}{(\beta_s \sqrt{\pi a})^m} = \int_{a_{og}}^{a_g} \frac{da}{(f\beta_g \sqrt{\pi a})^m} \tag{12}$$

Note that Eq. (12) is independent of stress history (explicitly), so the a_s versus a_g response is also anticipated to be independent of stress history. Also note that the constants C_g and C_s from Eq. (9) have been retained in Eq. (12). This permits the use of two different materials for the gage and structure. It will also permit designers to account for variability in material properties if the same metal is used in both structure and gage.

A numerical integration scheme was employed here to solve Eq. (12) for a_s as a function of a_g. First, the integration of the right-hand side of Eq. (12) was carried out with the trapezoidal rule together with Romberg's extrapolation method. The upper bound of the absolute error for this procedure was specified to be less than 1×10^{-5}. Next, an upper limit for the left-hand side of Eq. (12) was chosen and the integration performed as before. Depending on the agreement of the left-hand value with the previously determined right-hand side, an adjustment was made in the upper limit (a_s) of the left integral and the process repeated until the values of the two integrals agreed to within 0.02%.

SECTION III

EXAMPLE RESULTS

Solving Eq. (12) by the numerical procedure described above, the relation between structural and gage flaw lengths was found for several geometric configurations. Results from the sample cases are briefly described below. In all examples, the structure and gage had the same C, E, and m, while Poisson's ratio for the gage was 0.333.

Consider an edge cracked coupon (50 mm long by 25 mm wide) attached to a large plate containing a 6.4 mm diameter radially cracked hole (length = 1.3 mm) as shown in Figure 3. Numerical results from Eq. (12) for m = 4 (a constant amplitude fatigue crack growth rate exponent typical of many structural materials) are shown in Figure 3 for various initial gage flaw sizes (a_{og} = 1.3, 1.9, 2.5 and 3.8 mm). Note that the results show a strong dependence on initial crack size, varying from a fast growing structural crack ($a_{og} = a_{os}$ = 1.3 mm) to a response where gage crack growth significantly amplifies corresponding extension of the structural flaw (a_{os} = 1.3 mm and a_{og} = 3.8 mm). Thus, varying the initial crack size provides one means for designing a gage for various degrees of amplification of structural crack growth.

Figure 4 shows the results obtained for a study similar to the one above, but with a gage containing a center crack rather than an edge crack. The material parameters and gage dimensions are the same as in the previous example. The variation in initial flaw sizes again demonstrates the two cases of a gage which is insensitive to structural crack growth (a_{go} = 1.3 mm) and one which is highly sensitive to structural flaw growth (a_{go} = 3.8 mm). However, for an initial gage flaw size of 2.5 mm the gage demonstrates growth characteristics which permit it to be usable over a wide range of flaw sizes in the structure, between 1.3 mm and 23 mm.

If the gage flaw is located in the structural component rather than in an attached coupon and sees the same remote stress, f = 1 in Eq. (12). Experimental data (Reference 12) for this special case, provided a means of checking Eqs. (9) to (12) of the model. Briefly, the experimental set-up was as follows:

Long specimens of 7075-T651 aluminum (width = 150 mm, thickness = 12.7 mm) containing both a radially cracked hole and a center crack in series as shown in Figure 5, were subjected to complex variable amplitude loading representative of an aircraft stress history. Since the crack growth exponent m was not known beforehand, computations were made for m = 3, 4, and 5; a range encompassing expected values for this material. Of course in practice, the value of the Paris exponent, m, would be a well documented constant from spectrum fatigue tests of the structure and gage material. Note in Figure 5 that these analytical predictions closely bound the test data. Thus this excellent agreement between experiment and analysis lends credence to the validity of Eq. (9), and subsequent development of Eq. (12). Again, it should be emphasized that the numerical calculations required no knowledge of the actual load history applied to the test specimen.

SECTION IV

CONCLUDING DISCUSSION

A new concept for monitoring flaw growth in structural components with a flawed gage has been presented along with a mathematical model for the relation between the structural and gage flaw sizes. This relationship, given by Eq. (12), and demonstrated in Figures 3-5, provides the means for designing a simple crack growth gage capable of "tail number" tracking a fleet of structures for extension of potential or known flaws. The proposed gage would have no moving or electronic components to malfunction, need only minimum instrumentation and could be designed for various degrees of amplification between structural and gage crack lengths.

Since Eq. (12) relates the gage crack length with the assumed structural flaw size and depends only on geometric factors and material properties, extensive records of service loads would not be required to estimate flaw growth. Indeed, the gage provides a direct measure of crack growth, acting as an analog computer which collects, stores, and analyzes the severity of the input loads, and then responds with the appropriate flaw extension. Thus, the loading conditions which affect flaw growth (i.e., stress level, overloads, temperature, environment, etc.) should be integrated in the gage prediction of structural crack length on a real time basis. Although extensive experimental testing of this gage capability remains for future work, it is encouraging that the data shown in Figure 5 provide a preliminary verification of the transfer function model described in Eq. (12).

The authors believe that the crack gage described can be used by logistics management for maintenance decisions in both of the following two ways: (1) as a simple "go/no go" measure of the necessity for inspecting or modifying any given structure, or (2) in conjunction with a Normalized Crack Growth Curve (Reference 11). The crack gage-structural crack transfer function (Eq. (12)) and the Normalized Crack Growth Curve associated with the structural crack would collectively provide a direct indication of structural crack size and an estimation of remaining useful service life. This second decision making concept is explored more fully in Reference 12.

While this work concentrated on metallic structure, this concept could potentially be used to predict the residual life of composite structural components. In this case, the use of the crack growth analogy may have to be avoided because it has been shown that composites rarely fail by the growth of a single dominant crack (Reference 13). Instead, composites seem to accumulate damage via the growth of many fine cracks, delaminations, etc. around pre-existing flaws or stress concentrations. It might have been possible to account for this type of damage accumulations in the above mathematical model if a unified theory for damage accumulation in composites existed. Unfortunately it does not, thereby preventing our extension of the crack growth gage concept to these materials.

REFERENCES

1. A. P. Shewmaker and J. A. Wagner, Proc. Air Force Conference on Fatigue and Fracture of Aircraft Structures and Materials, AFFDL-TR-70-144, WPAFB, Ohio, 1970, 833.
2. D. H. Whitford and R. J. Dominic, Proc. Air Force Conference on Fatigue and Fracture of Aircraft Structures and Materials, AFFDL-TR-70-144, WPAFB, Ohio, 1970, 847.
3. T. L. Haglage and H. A. Wood, Proc. Air Force Conference on Fatigue and Fracture of Aircraft Structures and Materials, AFFDL-TR-70-144, WPAFB, Ohio, 1970, 137.
4. D. R. Harting, Experimental Mechanics, 6, 1966, 19A.
5. J. C. Spanner and McElroy, Ed., Monitoring Structural Integrity by Acoustic Emission, ASTM STP 571, 1975.
6. M. D. Coffin and C. F. Tiffany, Journal of Aircraft, 13, 1976, 93.
7. C. E. Browning, G. E. Husman, and J. M. Whitney, Composite Materials Testing and Design (Fourth Conference), ASTM STP, American Society for Testing and Materials, 1976.
8. D. H. Kaelble, P. J. Dynes, and L. Maus, "Hydrothermal Aging of Composite Materials; Part 1, Interfacial Aspects," Journal of Adhesion, In Press.
9. D. H. Kaelble, P. J. Dynes, and L. Maus, "Hydrothermal Aging of Composite Materials; Part 2, Matrix Aspects," ibid.
10. H. Okamura, K. Watambe, and T. Takano, Progress in Flaw Growth and Fracture Toughness Testing, ASTM STP 536, 1973, 423.
11. J. P. Gallagher and H. D. Stalnaker, Proc. AIAA/ASME/SAE 17th Structures, Structural Dynamics and Materials Conference, Valley Forge, PA, 1976, 486.
12. J. P. Gallagher, A. F. Grandt, and R. L. Crane, "Tracking Crack Growth Damage at Control Points, " paper in preparation for presentation at AIAA/ASME/SAE 18th Annual Structures, Structural Dynamics and Materials Conference, March 1977.
13. N. J. Pagano, Private Communication, AFML/MBM, WPAFB, Ohio 45433.

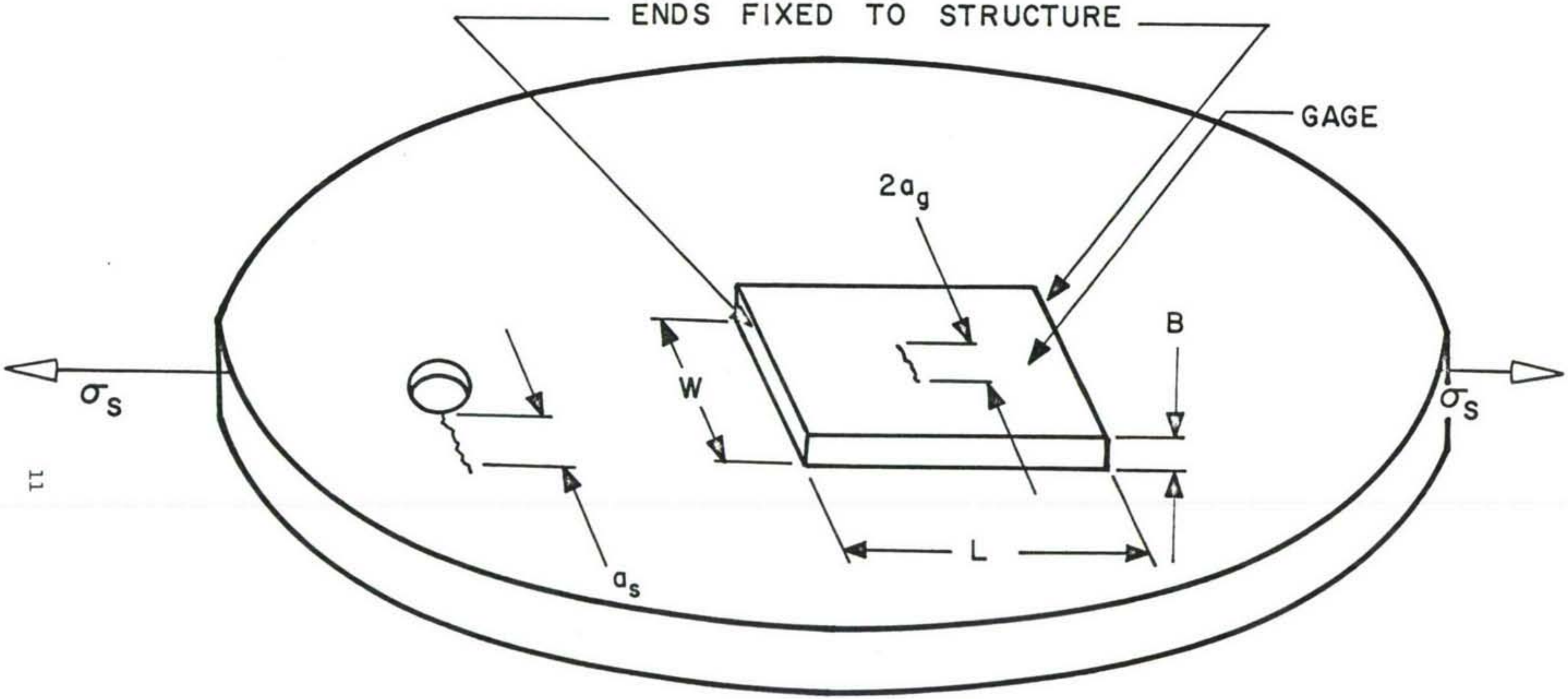

Figure 1. Schematic View of Crack Growth Gage Attached to Flawed Structural Component.

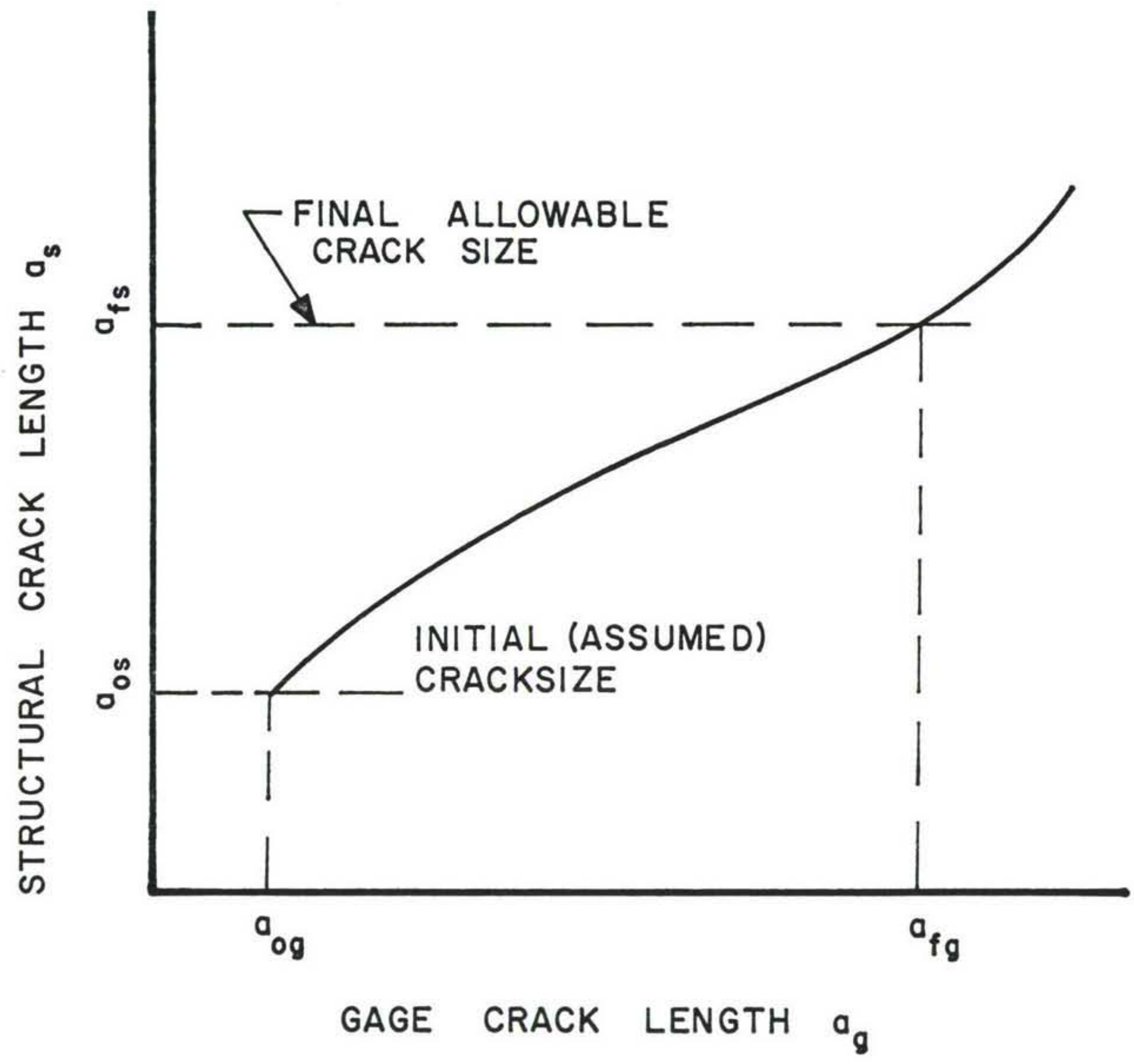

Figure 2. Schematic Representation of the Relationship Between the Gage and Structural Flaw Sizes.

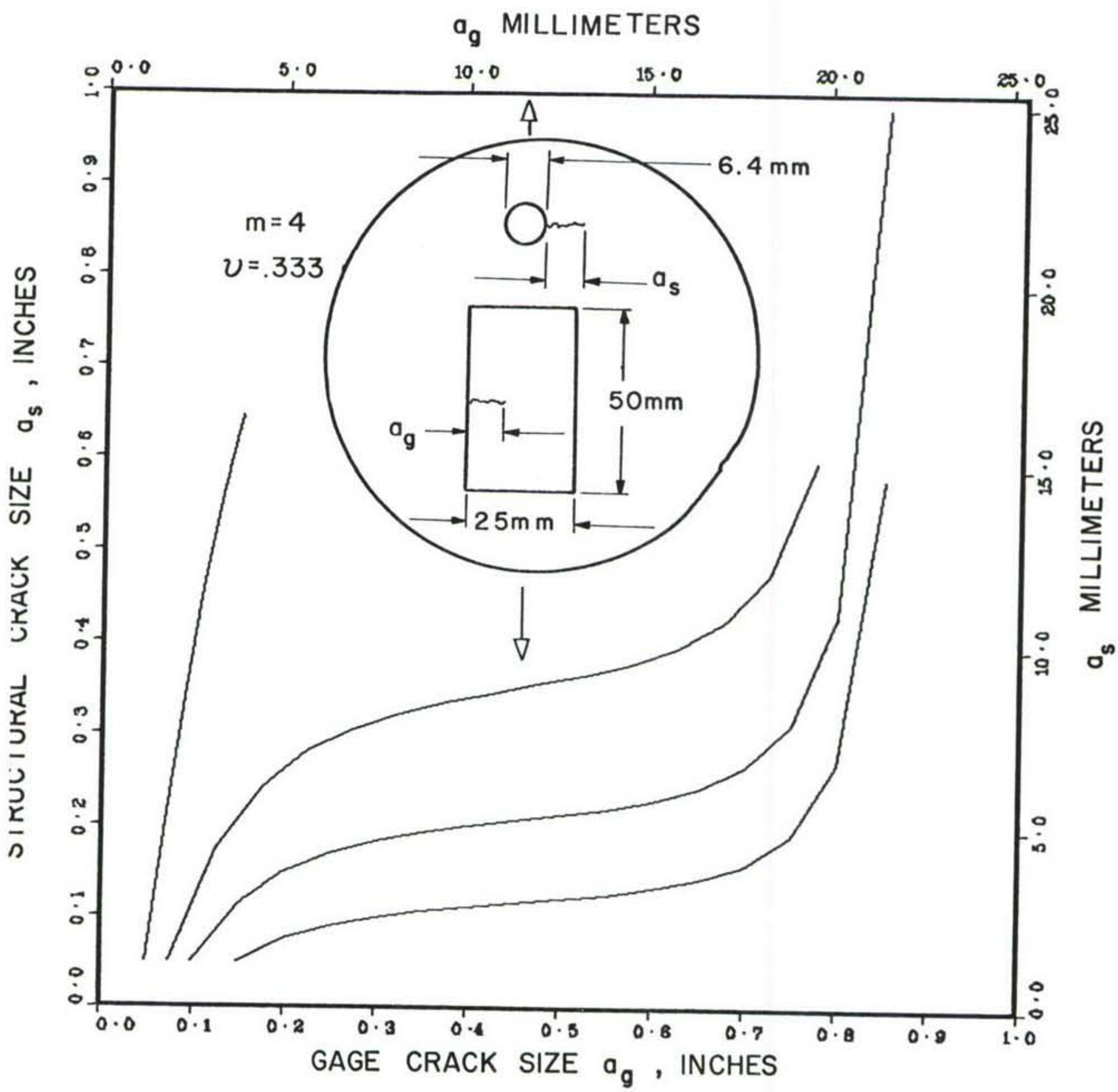

Figure 3. Analytical Results Showing the Effect of the Initial Gage Flaw Size on a Typical Gage/Structural Crack Growth Relationship.

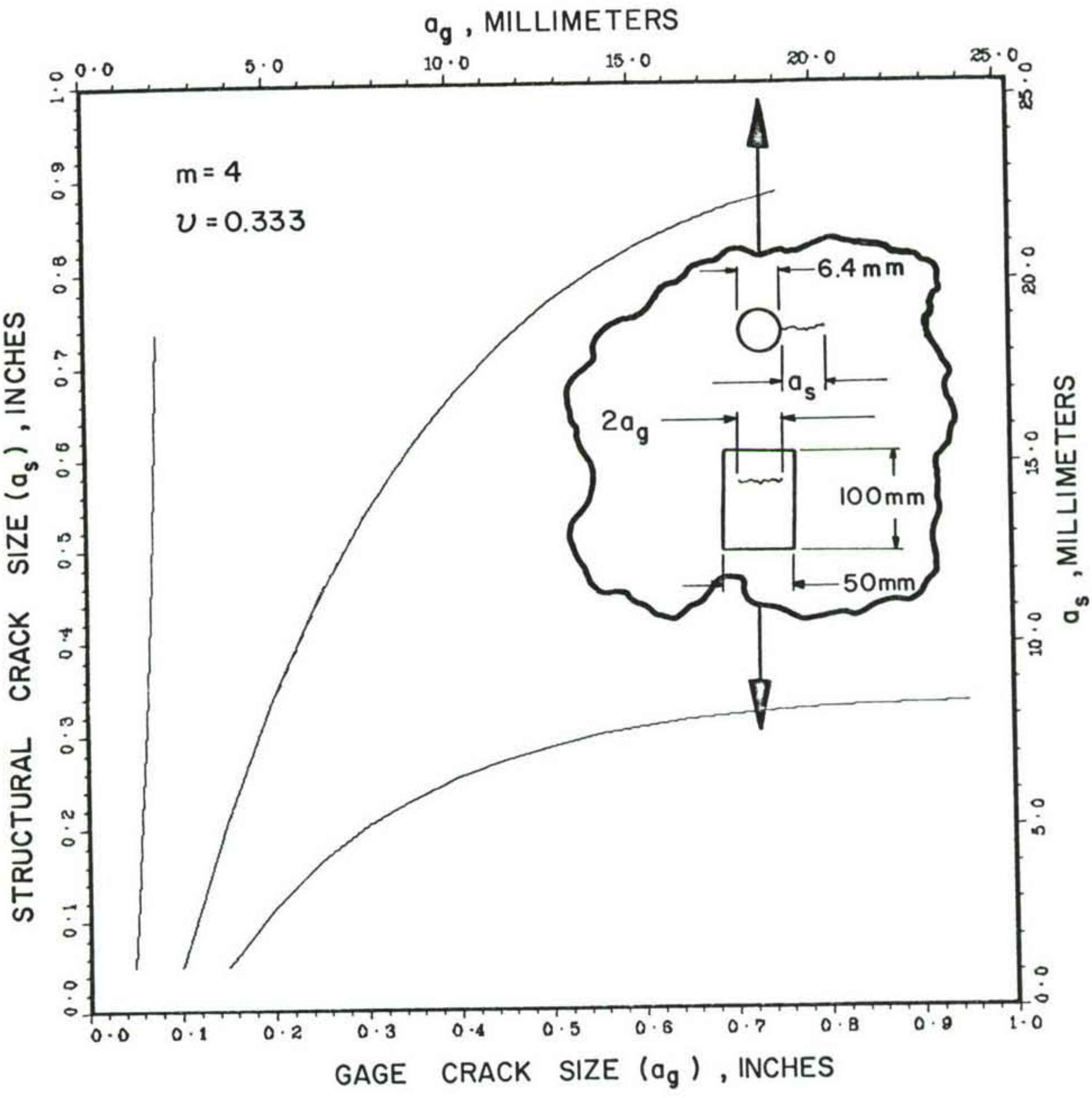

Figure 4. Analytical Prediction of a Crack Growth at a Hole as a Function of Crack Size in a Center Cracked Gage.

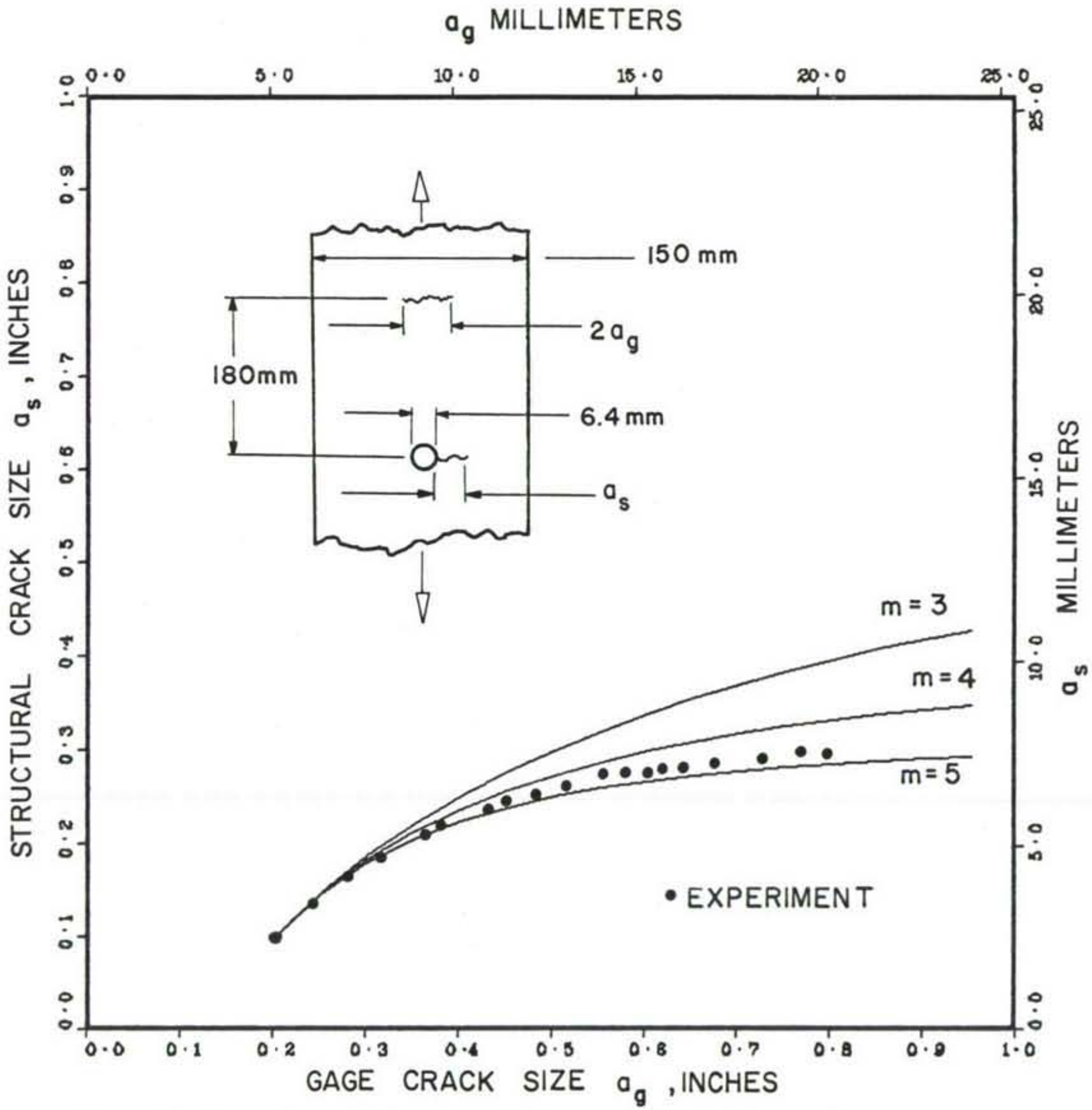

Figure 5. Comparison of Experimental Data with the Analytical Prediction for the Relationship Between Two Different Flaw Geometries in the Same Specimen (f=1, Eq. 12). The Specimen Was Subjected to Spectrum Loading.

☆ U. S. GOVERNMENT PRINTING OFFICE: 1976 — 757-001/63